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REFORMING CATALYSTS AND METHODS OF ALCOHOL STEAM REFORMING

FIELD OF THE INVENTION

The invention relates to catalysts and methods of steam reforming alcohols.

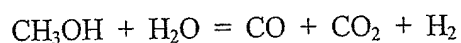
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BACKGROUND OF THE INVENTION

The use of hydrogen gas (H₂) fueled fuel cells such as polymer electrolyte membrane fuel cells (PEMFCs) offer the potential of reducing carbon dioxide (CO₂) and eliminating nitric oxide emissions from vehicles. However, current technology does not offer economically attractive options for storage of enough hydrogen gas to deliver the driving range to which motorists are accustomed. Instead of carrying a tank of hydrogen gas, vehicles could carry a tank of liquid fuel such as an alcohol. The alcohol, typically methanol, would pass through a fuel processor that converts the methanol to hydrogen gas that immediately passes to the fuel cell. In this fashion, hydrogen-powered vehicles need not carry any hydrogen tanks.

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The process for converting methanol to hydrogen is known as "steam reforming" and is described by the following (unbalanced) chemical equation:



To operate efficiently, the steam reforming reaction must be run in the presence of a catalyst. It has been reported by Isawa et al. that Pd/ZnO is a highly selective catalyst for steam reforming of methanol. See Catal. Lett. 19, 211-216 (1993).

The development of better steam reforming catalysts has long been an area of intense interest. An example of some recent research appears in published patent application EP 1 061 011 A1. In this publication, Wieland et al. report a supported PdZn/ZnO catalyst for methanol steam reforming. A catalyst (Example A) was made by wash coating gamma-alumina onto a ceramic honeycomb, impregnating the gamma-alumina with an aqueous solution containing Pd(NO₃)₂ and Zn(NO₃)₂, followed by drying, calcining at 500 °C and reducing at 400 °C. The examples in this publication used a steam-to-carbon ratio of 1.5 and a liquid hourly space velocity (LHSV) of 5 h⁻¹. Assuming a density of 0.96 g/ml for the feed, and assuming 100% conversion

(note that the substantial increase in productivity from 300 to 350 °C indicates that conversion at 300°C is substantially below 100% conversion), the maximum possible hydrogen productivity would have been 5500 ml H₂/ml cat-hr.

For the purpose of developing an efficient fuel processor, weight and size of the energy device are major considerations. In order to reduce overall size of the on-board power system, insulating material should be minimized. This requires that steam reformer to be operated at relatively low temperature.

SUMMARY OF THE INVENTION

The present invention provides catalysts of at least 4 types: (1) palladium on zinc oxide (Pd/ZnO) on a large pore support (Pd/ZnO/support); (2) palladium-ruthenium or palladium-zinc alloy on alumina or zirconia (Pd-Ru or Pd-Zn/Al₂O₃ or ZrO₂); (3) a catalyst comprising copper, zinc, palladium or ruthenium on a cerium promoted alumina or zirconia support; and (4) Pd on ZnO on a metal oxide support, characterized by a hydrogen productivity of at least 10,000 ml H₂/ml cat-hr, when tested according to the procedure set forth in the Examples section.

The invention also provides methods of alcohol steam reforming, reactors, and fuel processing systems that use these catalysts.

In one aspect, the invention provides a method of methanol steam reforming in which methanol and water vapor contact a catalyst; wherein the catalyst contains a palladium on zinc oxide catalyst and where at least 20% of the catalyst's pore volume is composed of pores in the size range of 0.1 to 300 microns. Neither powders nor pellets possess this type of porosity. Preferably, this reaction forms hydrogen from the reaction of said methanol and water vapor at a rate of at least 1.5 mole methanol per gram catalyst per hour (1.5 mole methanol / (g catalyst)(hr)).

In another aspect, the invention provides a fuel processing system comprising a fuel tank connected to a reactor and a reactor connected (either directly or indirectly) to a fuel cell. The reactor contains a palladium on zinc oxide catalyst where at least 20% of the catalyst's pore volume is composed of pores in the size range of 0.1 to 300 microns. The fuel cell is connected to the reactor such that hydrogen gas generated in the reactor

can flow into the fuel cell either (1) directly or (2) indirectly with the use of down stream processing to either produce additional hydrogen in a water gas shift reactor and/or a secondary clean up process to reduce carbon monoxide levels or purify the hydrogen prior to entering the fuel cell.

5 In another aspect, the invention provides a method of alcohol steam reforming in which methanol and water contact a catalyst; where the catalyst comprises palladium or ruthenium on cerium-promoted zirconia or alumina. Hydrogen is formed from the reaction of the methanol and water vapor over the catalyst.

10 In a further aspect, the invention provides a catalyst that includes: a metal oxide support; a coating comprising zinc on the metal oxide support; and palladium in contact with the coating. This catalyst possesses a volumetric productivity of at least 10,000 ml H_2 / ml catalyst·hr. Preferred supports include: alumina, titania, and zirconia. The weight % of the support in the catalyst is preferably 50 to 90%, preferably with 10 to 30 wt. % ZnO (measured based on elemental analysis for Zn, assuming all Zn is in the form of
15 ZnO), and, preferably, 1 to 15 wt% Pd. For powders (and crushed pellets, etc.), volumetric productivity is measured in a reactor with a 5 mm inner diameter, at 300 °C with premixed, vaporized water and methanol at a water to methanol ratio of 1.78, about 1 atm pressure and a contact time of 100 milliseconds (ms). For engineered catalysts, volumetric productivity is measured analogously except at a contact time (based on
20 reactor volume) of 150 ms and where the engineered catalyst is sized to 5 cm x 0.94 cm x 0.3 mm (thickness is 0.3 mm) (or less, if unable to obtain this size) and placed in a channel having dimensions 2"x 0.37"x 0.05", 5 cm x 0.94 cm x 0.13 cm) that is located in (i.e., a rectangular aperture machined in) the center of a stainless steel catalyst holder having a diameter of 1.3 cm. Typically, two engineered catalysts were separated with a
25 spacer and inserted into the channel. The spacer also holds catalysts against the walls of channel. More preferably, the catalyst has a productivity of at least 40,000, more preferably at least 60,000 and in some embodiments a productivity of 20,000 to 90,000. The invention also includes a method of alcohol steam reforming comprising passing water and an alcohol in contact with the above-described catalyst. Preferably, the steam
30 reforming reaction is carried out in a temperature range of 220-350 °C, more preferably

250 to 320 °C. The invention also includes alcohol-reforming catalyst systems in which the catalyst is present along with an alcohol and water, and, optionally, a reactor.

The invention also provides a method of making a catalyst that includes the steps of: providing a solid metal oxide support; adding a solution comprising dissolved zinc to the solid metal oxide support; adding a base to increase pH; and subsequent to at least a portion of the step of adding a base, depositing Pd. Preferred supports include: alumina, titania, and zirconia. The metal oxide support could itself be deposited (either before or after the other steps) onto a large pore support. This method is especially advantageous in aqueous solutions where the metal oxide support would normally have an acidic surface.

10 The dissolved Zn is at least partially, and more preferably completely, dissolved in a solvent. The solution containing dissolved zinc contains at least zinc, but may also contain other components including metals; in some preferred embodiments there are no other metals in the zinc solution; in some preferred embodiments the solution is 0.1 to 3 M zinc. The order of addition, solid oxide to Zn solution or Zn solution to solid oxide is not critical and the inventive method includes either order. The base can be added before, during or after the zinc solution is added. Preferably, the base is added after the zinc solution, more preferably it is added to slowly to result in gradual precipitation of zinc.

15 Preferably, the base is an aqueous ammonia solution. In some preferred embodiments, base is added until a pH of 7 or greater is obtained. Improvement is obtained where Pd is added after at least a portion of the base is added. Preferably, Pd is added after all the base has been added - this results in the greatest percentage of Pd being disposed on the catalyst surface. Pd is preferably deposited on the catalyst after deposition of the zinc, and, in some preferred embodiments, after the zinc-containing layer has been dried and, optionally, calcined. In some preferred embodiments, Pd is impregnated onto the Zn-

20 containing support in solution, preferably aqueous solution. In some preferred embodiments, the catalyst is prepared and reduced under hydrogen with temperatures never exceeding 400 °C. preferably, calcining of the Zn-containing catalyst, either before and/or after depositing Pd, is conducted at 200 to 400°C, more preferably 250 to 350°C. Similar temperature ranges can be used when reducing (and operating) the catalyst. The

low temperature treatment increases catalyst life and surface area. The invention also includes catalysts made by the foregoing methods.

Various embodiments of the invention can provide numerous advantages including one or more of the following: high conversions at relatively short contact times, selectivity control, and low temperature operation.

The subject matter of the present invention is particularly pointed out and distinctly claimed in the concluding portion of this specification. However, both the organization and method of operation, together with further advantages and objects thereof, may best be understood by reference to the following description taken in connection with accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a plot of methanol conversion vs. catalyst bed temperature for a powder and felt-supported Pd/ZnO catalyst.

Fig. 2 is a plot of specific activity vs. temperature for a powder and felt-supported Pd/ZnO catalyst.

Fig. 3 is a plot of pressure drop for the powder and felt-supported Pd/ZnO catalysts.

Fig. 4 is a schematic of a simplified fuel cell system that includes a cross-sectional view of a water gas shift reactor that includes a microchannel heat exchanger.

Fig. 5 is a schematic of catalyst testing apparatus.

Fig. 6 is a plot of methanol conversion vs. catalyst bed temperature for a variety of powder catalysts.

Fig. 7 is a plot of hydrogen selectivity vs. catalyst bed temperature for a variety of powder catalysts.

Fig. 8 is a plot of CO selectivity vs. catalyst bed temperature for a variety of powder catalysts.

DESCRIPTION OF PREFERRED EMBODIMENTS

The steam reforming catalyst requires catalytically active surface sites that reduce the kinetic barrier to the alcohol steam reforming reaction. Preferably the active surface sites include palladium (Pd) and/or ruthenium (Ru), Cu, and Pd-Zn alloy that are dispersed over the surface. The catalyst preferably contains up to 30 wt% Pd, more preferably 2 to 10 wt%. In some embodiments, the catalyst preferably contains up to 10wt%, more preferably 0.2% to 5% weight percent Ru. Too little catalytically active metal, preferably Pd and/or Ru, can result in too few catalytic sites, while too much is costly due to lower dispersion.

The surface active sites are dispersed on a (preferably high surface area, BET surface area $>10\text{m}^2/\text{g}$) metal oxide support. Preferred metal oxides include ZnO , ZrO_2 , and Al_2O_3 . The metal oxide, including the presence of catalytically active surface sites, as measured by BET, preferably has a volumetric average pore size of less than 0.1 micrometer (μm). The metal oxide, including the presence of catalytically active surface sites, as measured by BET, nitrogen physisorption, preferably has a surface area of more than $10\text{ m}^2/\text{g}$, more preferably a surface area of 20 to $500\text{ m}^2/\text{g}$. The metal oxide can be particles, preferably having diameters less than 4 mm, more preferably less than 1 mm, or, more preferably the metal oxide forms a layer (of agglomerated particles or a continuous film) having a thickness less than 4 mm, more preferably less than 1 mm, and still more preferably a thickness of less than $40\text{ }\mu\text{m}$ on large pore supports.

The catalyst may take any conventional form such as a powder or pellet. In some preferred configurations, the catalyst includes an underlying large pore support. Examples of preferred large pore supports include commercially available metal foams and, more preferably, metal felts. The large pore support has a porosity of at least 5%, more preferably 30 to 99%, and still more preferably 70 to 98%. Preferably, the support has a volumetric average pore size, as measured by BET, of $0.1\text{ }\mu\text{m}$ or greater, more preferably between 1 and $500\text{ }\mu\text{m}$. Preferred forms of porous supports are foams and felts and these are preferably made of a chemically and thermally stable and conductive material, preferably a metal such as stainless steel or FeCrAlY alloy. These porous

supports are preferably thin, such as between 0.1 and 1 mm. Foams are continuous structures with continuous walls defining pores throughout the structure. Felts are fibers with interstitial spaces between fibers and includes tangled strands like steel wool. Various supports and support configurations are described in U.S. Patent Applications
5 Ser. No. 09/640,903 (filed Aug. 16, 2000), U.S. Patent No. _____ which is incorporated by reference.

The catalyst with a large pore support (and including the spinel-supported catalyst) preferably has a pore volume of 5 to 98%, more preferably 30 to 95% of the total porous material's volume. Preferably, at least 20% (more preferably at least 50%) of
10 the material's pore volume is composed of pores in the size (diameter) range of 0.1 to 300 microns, more preferably 0.3 to 200 microns, and still more preferably 1 to 100 microns. Pore volume and pore size distribution are measured by mercury porosimetry (assuming cylindrical geometry of the pores) and nitrogen adsorption. As is known, mercury porosimetry and nitrogen adsorption are complementary techniques with mercury
15 porosimetry being more accurate for measuring large pore sizes (larger than 30 nm) and nitrogen adsorption more accurate for small pores (less than 50 nm). Pore sizes in the range of about 0.1 to 300 microns enable molecules to diffuse molecularly through the materials under most gas phase catalysis conditions.

In one embodiment, the large-pore substrate has a corrugated shape that could be
20 placed in a reaction chamber (preferably a small channel) of a steam reformer.

One preferred method of making the catalyst is by impregnating a metal oxide with solutions containing the desired metals, typically Pd and/or Ru and Ce (if present) followed by drying, calcining, and reducing. Other methods could be used. For example, it is also anticipated that catalyst with the aforementioned preferred compositions can be
25 prepared by a co-precipitation method using inorganic or organometallic precursors.

When an underlying, large-pore substrate is used, the powder can be slurry coated over the substrate at any stage in the preparative process. For example, a high surface area metal oxide could be slurry coated onto the substrate followed by depositing, drying and activating a metal via the impregnation method. Alternatively, a vapor coat or soluble
30 form of alumina (or other high surface area material) could be applied onto the substrate.

Although solution or slurry coating is typically less expensive, vapor coating of the various materials could also be employed.

In a method of making a catalyst in which Pd is deposited on a Zn-containing metal oxide support, it has been surprisingly discovered that a superior-performing catalyst is obtained when pH is increased prior to deposition of Pd. It is believed that this procedure allows zinc hydroxide to form, resulting in better catalyst characteristics in the final catalyst.

The present invention also provides methods of steam reforming in which an alcohol is reacted with water vapor at short contact times over the catalysts described above. The contact time is preferably less than 1 s, more preferably 10-500 milliseconds (msec).

The alcohol steam reforming reaction is preferably carried out at 200-500°C, more preferably 240-400°C. The reaction can be run over a broad pressure range from sub-ambient to very high. The alcohol is a C₁-C₁₀ alcohol, preferably methanol.

Certain aspects of the invention can best be described in terms of properties such as conversion, selectivities, specific activity, and pressure drop. In preferred embodiments, the catalyst, when tested at short contact times in the apparatus schematically illustrated in Fig. 5, or equivalent apparatus, shows good alcohol conversions, selectivities, specific activity and low pressure drop.

Alcohol conversion is preferably at least 50%, more preferably at least 80% and still more preferably at least 90%. Hydrogen selectivity, defined as moles H atoms in H₂ in the product gas divided by moles H in all product gases, is preferably at least 50%, more preferably at least 60%, still more preferably at least 85%.

Preferred embodiments of the inventive catalysts and methods may also be described in terms of their exceptionally high specific activity. Preferably, the catalyst and/or method has a specific activity of greater than 1.5 mol methanol converted/(g catalyst)(hr) when tested at 400C, 25 msec contact time, 1.8 steam-to-carbon ratio; and the catalyst exhibiting this specific activity preferably has a pressure drop of less than 25 psig.

One embodiment of a reactor 2 is shown in cross-section in Fig. 4. The reaction chamber 4 contains catalyst 6 and has an inlet 8 and outlet 10. In Fig. 4, the catalyst is shown on the top and bottom of the reaction chamber with an open channel from the reactor inlet to the outlet - this configuration is called "flow-by." Other configurations, such as "flow-through" where flow is directed through a porous catalyst, are, of course, possible. To improve heat transfer, a microchannel heat exchanger 12 can be placed in contact with the reaction chamber. The microchannel heat exchanger 12 has channels 14 for passage of a heat exchange fluid. These channels 14 have at least one dimension that is less than 1 mm. The distance from the channels 14 to catalyst 6 is preferably minimized in order to reduce the heat transport distance. Microchannel heat exchangers can be made by using known techniques which include such methods as electrodischarge machining (EDM), wire EDM, conventional machining, and the like. An example of example fabrication methods is described in Tonkovich et al., 1997, Proceedings of the 2nd International Conference on Microreaction Technology, p. 45-53.

The preferred reaction chamber for the steam reforming reaction may be of any length or height. The preferred reaction chamber width is less than 2 mm. More preferably the reaction chamber width is less than 1 mm. The reaction chamber is preferably in thermal contact with a heat exchange chamber. The heat exchange chamber in thermal contact with the reaction chamber may also be of any length or height. Preferably the length and height of the heat exchange chamber is close to the dimensions of the reaction chamber. Most preferably the heat exchange chamber is adjacent to the reaction chamber in an interleaved chamber orientation (width is the direction in which the interleaved reaction chambers and heat exchangers stack). The width of the heat exchanger chamber is preferably less than 2 mm. More preferably the width of the heat exchange chamber is less than 1 mm. The direction of flow in the heat exchange chamber may be either co-current, counter-current, or cross-flow. This approach will enable excellent heat transfer performance.

The alcohol reforming reactor may also be configured by placing the reaction chamber adjacent to a heat exchanger chamber that is comprised of an array of microchannels rather than a single microchannel. In this configuration the width of the

reaction chamber may exceed 2 mm, but at least one dimension of a single microchannel in the array must be less than 2mm. Preferably this dimension is less than 1mm. The allowable width of the reaction chamber is a strong function of the effective thermal conductivity of the catalyst insert. The higher the effective thermal conductivity, the wider the insert to enable rapid heat removal. For effective thermal conductivities on the order of 2 W/m/K, it is anticipated that the maximum reaction chamber width must remain less than 2 mm and preferably 1 mm. The advantage of this design approach is easier manifolding, fluid connections, and catalyst loading; but this approach may result in a reduction in heat transfer performance. In some system configurations and embodiments the simpler manifolding may result in a lower system cost that offsets the reduction in heat transfer performance.

In preferred embodiments, the reaction chamber 4 is connected to fuel tank 16 such that alcohol from the tank can flow into the reaction chamber. Although a fuel tank is shown in the Figure, it should be recognized that any alcohol fuel source, such as a pipeline could be used. The liquid fuel stream may flow through a separate vaporizer or be vaporized within a section of the steam-reforming reactor. In some preferred embodiments the alcohol is vaporized in a microchannel vaporizer and/or preheated in a microchannel preheater. The product gases (including H₂) then may either flow into fuel cell 22 where the H₂ is combined with O₂ to generate electricity, or the product of the methanol reforming reactor may flow into a water gas shift reactor to convert some of the carbon monoxide into carbon dioxide and additional hydrogen. This stream may flow directly into a fuel cell 22, or may flow into a secondary clean up process to further purify hydrogen or reduce carbon monoxide to a level that can be accommodated in a fuel cell. The secondary clean-up process may include a preferential oxidation reactor, membrane separation of either hydrogen or carbon monoxide, a sorption based separation system for either hydrogen or carbon monoxide, and the like. These elements form a highly simplified fuel processing system 30. In practice, fuel processing systems will be significantly more complex. Typically, heat from a combustor will be used to generate heat for other processes such as generating steam (not shown) that can be utilized for steam reformer and/or water gas shift reactor. Various fuel cells are well-known and

commercially available and need not be described here. Instead of fuel cell 22, the hydrogen-containing gas could go to: a storage tank, a refueling station, a hydrocracker, hydrotreater, or to additional hydrogen purifiers.

EXAMPLES

The following examples are generalized descriptions based on typical conditions used to make numerous samples. Certain temperature ranges, etc. set forth preferred ranges for conducting various steps.

Example 1: Synthesis of Ru-Al₂O₃ catalyst (Comparative Example)

The incipient wetness technique was employed to deposit Ru metal onto the alumina support. Initially, an alumina support was treated by oxidatively calcining gamma alumina at a temperature of about 350 to 550 °C to remove water from the micropores of the support. Meanwhile, aqueous Ru solution was prepared by diluting Ru(III)nitrosyl (obtained from Aldrich Chemical Co. as an aqueous solution of dilute nitric acid containing 1.5 wt% Ru) with DI water. Alternatively, non-aqueous Ru solution could be used by dissolving an organic Ru compound in an organic solvent such as acetone. The target Ru concentration in the fired catalyst was 1-3 wt%. For single step impregnation, the amount of Ru solution utilized was an amount that is at least equivalent to the pore volume of the alumina utilized. The impregnated catalyst was dried at a temperature of 100°C for a period of 12 hours in air so as to spread the metal over the entire support. The dried catalyst was calcined by heating slowly in air at rate of 2°C/min, to a temperature in the range of 300 to 500°C, that is sufficient to decompose the metal salts. The aforesaid drying and calcinations steps can be done separately or can be combined.

The foregoing impregnation steps were repeated with additional impregnation solutions in order to obtain the desired metal loading. After the last impregnation sequence and calcination, the Ru impregnated alumina, Ru-Al₂O₃, was then subjected to an activation treatment, preferably reduction in the presence of hydrogen at 300-400°C.

Example 2: Synthesis of Pd-Ru/CeO-ZrO₂

Cerium oxide was impregnated on ZrO₂ using Ce(NO₃)₃ hexahydrate from Aldrich. The desired concentration of Ce was from 1 to 3 wt%. After impregnation, the Ce promoted ZrO₂ was dried and calcined according to the procedure described in above examples. Pd and Ru were co-impregnated on CeO-ZrO₂. Pd(NO₃)₂ solution containing 20wt% Pd (Engelhard) was mixed with 1.5 wt%Ru(III)nitrosyl (Aldrich) at a pre-determined ratio. The amount of Pd-Ru solution utilized was an amount at least equivalent to the pore volume of the CeO-ZrO₂ utilized. Depending on desired metal loading, sequential impregnation (multi-step impregnation) may be used by repeatedly adding Pd-Ru solution. Between each impregnation step, catalyst was dried and calcined. After the last impregnation and calcinations sequence, the metal impregnated catalyst support was subjected to an activation treatment, preferably reduction at 300-500°C.

Example 3: Pd/ZnO and Pd-ZnO on Al₂O₃

Pd/ZnO catalyst is prepared by impregnating Pd(NO₃)₂ solution (Engelhard, 20 wt% Pd) on ZnO oxide (Aldrich). Typical Pd loading varied from 5 to 20 wt%. The impregnation procedure was similar to that used in the above examples. After impregnation, the catalyst was calcined at 350-550 °C.

Pd-ZnO can be coated on a high surface area support such as Al₂O₃. Coating Pd-Zn on Al₂O₃ enhances available surface area so as to increase the number of active sites. First, a thin layer of ZnO is formed on Al₂O₃ surface. This can be done by soaking 2.0 gram of Al₂O₃ in 0.5M Zn(NO₃)₂ solution, followed by drying at 100°C and calcining at 350 °C. After a thin layer of ZnO is formed on the surface, Pd is introduced by impregnating ZnO-Al₂O₃ with Pd(NO₃)₂. The amount of Pd(NO₃)₂ used depends on the desired loading of Pd which varies from 5 to 20 wt %. The catalyst was subjected to final calcinations in air at 350-650°C. Prior to steam reforming reaction, the catalyst should be reduced by hydrogen at 125-500°C. Different from above sequential impregnation, Pd nitrate and Zn nitrate can be co-impregnated on alumina. A Pd and Zn nitrate solution is prepared at a pre-determined ratio, the solution that contains both Pd and Zn can be impregnated on Al₂O₃.

Example 4: Engineered steam reforming catalyst

Catalyst was coated on FeCrAlY felt (obtained from Technetics, Deland, FL) using a wash-coating technique. Catalyst in the powder form was prepared using methods described in examples 1-3. Catalyst coating slurry was prepared by mixing powder catalyst with de-ionized water in the ratio of 1:6. The mixture was ball-milled for 24 hours to obtain coating slurry containing catalyst particles less than 1 micron. Before wash coating, metal felt is pretreated by a rapid heating to 900°C in air for 2 hours. The heat-treated felt was wash-coated by dipping the felt into catalyst slurry. The wash coating process may be repeated to obtain desired weight gain. Between each coating, the felt coated with catalyst was dried in an oven at 100°C for 1 hour. The coating procedure is repeated to achieve desired coating thickness. After the final coating step, the catalyst was dried overnight in an oven at 100°C and calcined by heating slowly in air at rate of 2°C/min to a temperature in the range of 300 to 500°C. The amount of catalyst coated was measured to be 0.1 gram catalyst per square inch (6.5 cm²) of felt. After coating, the felt coated with catalyst was calcined at between 300-500°C for 3 hours in air. Prior to steam reforming testing, the engineered catalyst felt was subjected to an activation treatment, preferably reduction at 300-400°C.

The above procedure can be applied to metal foams made of stainless steel, copper, alloys, etc.

Experimental Steam Reforming Testing Procedure

Steam reforming of methanol was carried out in a conventional fixed-bed down flow reactor. The reactor used for powder testing has an inside diameter of 5 mm. Typical catalyst loading was 0.06 gram of 70-100 mesh particles. The dimension of the channel is 2"x0.37"x0.03" (5cm x 0.94cm x 0.13cm; length x height x width). The steam reforming reaction was conducted between 220-475°C and atmospheric pressure. Prior to the reaction, catalysts were reduced in a 10% hydrogen stream in the temperature range from 125 to 350°C at atmospheric pressure. A mixture of N₂/H₂ was fed during start-up to establish steady state flow and to heat the reactor to a desired temperature. When

catalyst bed temperature reached the target, premixed methanol and water with $\text{H}_2\text{O}/\text{CH}_3\text{OH}$ molar ratio of 1.78 were vaporized in a preheater and fed into the reactor. H_2 flow was discontinued while N_2 flow continued to stabilize feed flow. Total feed flow rate was set to give desired contact time. When desired the contact time was fixed at 100 msec, total flow rate was set at 363 ml/min. A schematic diagram of the testing apparatus is shown in Fig. 5. The reaction products were analyzed by on-line GC. Methanol conversion was calculated based on feed and product flow rates and carbon balance. The selectivity was also evaluated based on carbon balance: CO selectivity = $[\text{CO}]/([\text{CO}] + [\text{CO}_2] + [\text{CH}_4])$.

When testing engineered catalyst, two felts (2"x 0.35" x 0.01") were placed in the single channel device (2"x 0.37" x 0.03") with a close contact with wall and a 0.01" gap in between. The single channel device is a pellet made of stainless steel with diameter of 0.5 inch (1.3 cm).

Steam reforming experiments were conducted to evaluate the effectiveness of both powdered and engineered catalysts. All catalysts were evaluated in a single channel device (2"x 0.37" x 0.03", 5 cm x 0.94 cm x 0.08 cm). Powdered catalyst with a particle size in the range of 70-100 mesh was packed inside the channel with a length of 2 inches (5 cm). Two engineered catalysts (2"x 0.35" x 0.01", 5 cm x 0.89 cm x 0.03 cm) were inserted within the single channel device and in contact with channel with a gap of 0.0254 cm in between. The single channel device was placed in a tube furnace. Reactants were preheated in the top zone of the furnace, and were introduced into the single channel device in a down-flow mode. Steam reforming of methanol was conducted at a fixed contact time, a steam-to-carbon ratio of 1.8/1, and a temperature maintained at 250 to 500 °C (chamber temperature was continuously monitored by a thermocouple). Effluent flowrate was measured by a bubble flowmeter, and product was analyzed using gas chromatography. Steam reforming activities of powdered Pd/ZnO catalyst and engineered catalyst are compared. As shown in figures 1-3, under the same conditions, powdered catalyst showed relatively higher methanol conversion (Figure 1). However, when specific activity, in terms of mol MeOH converted per gram of catalyst (Pd/ZnO) per hour, was compared (Figure 2), engineered catalyst is much more active. At lower

temperatures (250-350 °C), the advantage of using engineered catalyst is not significant, which is probably due to less mass transfer limitations and both engineered and powdered catalysts exhibit similar effectiveness factors. However, at higher temperatures (>350 °C), where mass transfer limitations are likely to predominate, engineered catalyst shows higher activity and the enhancement increases with temperature. This is probably due to less mass transfer limitations and improved catalyst effectiveness factor with engineered catalyst. Another plausible reason for the activity enhancement is likely due to the improved heat transfer with engineered substrate (FeCrAlY felt). It is envisioned that further enhancement in catalyst effectiveness factors, as a result of improvement in thermal conductivity, can be achieved using the felts consisted of metals with higher thermal conductivities such as Al, Cu, brass. In addition, an advantage of using engineered catalyst is also evidenced by lower pressure drop across the catalyst bed as shown in Figure 3, where maximum pressure drop for engineered catalyst is 20 psig while powder catalyst showed 35 psig pressure drop. Lower pressure drop is always desired.

Comparisons of 5 powder catalysts prepared as described above and a commercial catalyst (Cu/Zn/Al) are shown in Figs. 6-8. The commercial catalyst and the 3 wt% Ru on alumina (●) exhibited the poorest performance as measured by methanol conversion. As can be seen from Fig. 6, it was surprisingly discovered that cerium-promoted catalysts perform better than the otherwise-identical catalysts that lacked the cerium promoter. It was also found that for a fixed metal loading, catalysts relatively rich in Pd performed better than catalysts relatively rich in Ru; for example, an 8 wt% Pd-2 wt% Ru / Al₂O₃ catalyst performed better than a 5 wt% Pd-5 wt% Ru / Al₂O₃ catalyst. Excellent conversions were also obtained for a Pd/ZnO powder catalyst. Surprisingly, Pd/ZnO on a large pore support was found to exhibit superior specific activity as compared with the powder catalyst, even at lower pressure drops and identical contact times. The performances of Pd/ZnO or other methanol steam reforming catalysts can be further improved by optimizing the mass and heat transfer characteristics of the engineered ("engineered" refers to catalysts having a large pore support) catalysts.

Example 5

Alumina (BET surface area 220 m²/g, Engelhard Corp.) was heated at 5 °C per minute to 500 °C and maintained for 2 hours. One gram of the calcined alumina was added to 69 ml of 1M zinc nitrate solution at room temperature. The resulting slurry was stirred at room temperature on a stirring plate. Ammonium hydroxide was added dropwise into the slurry while the pH of the solution was monitored. This allows Zn to precipitate onto the alumina (presumably as a hydroxide). Ammonium hydroxide was added until the solution reached pH 8. The slurry was then stirred 1.5 hours. The solids were filtered off, washed with deionized water and dried in a vacuum oven at 110 °C overnight, then heated in air at 2 °C per minute to 350 °C and maintained for 6 hours. Next, the desired level of Pd was added from a 20 wt% Pd(NO₃)₂ solution (obtained from Engelhard Corp.) by the incipient wetness impregnation technique. Following addition of Pd, the solids were filtered off, washed with deionized water and dried in a vacuum oven at 110 °C overnight, then heated in air at 2 °C per minute to 350 °C and maintained for 6 hours.

For preparation of an engineered catalyst, the catalyst powder described above was combined with deionized water (in a water to catalyst weight ratio of at least 7) and comminuted with alumina grinding balls on a rotating device for at least one day. A FeCrAlY felt was cut and trimmed to size and pretreated by heating at 20 °C per minute to 900 °C and maintained for 2 hours to form a surface alumina layer. The resulting felt was dipped into the comminuted slurry then dried in vacuum at 110 °C for 20 minutes and repeating until reaching a target weight gain of 0.1 g per square inch (0.015 g per cm²) of (2"x 0.37"x 0.01", 5 cm x 0.94 cm x 0.3 mm - thickness is 0.3 mm) felt. After the final dip coat, the catalyst was dried 8 hours, then heated in air at 2 °C per minute to 350 °C and maintained for 6 hours.

The catalysts of Example 5 were tested in a conventional fixed-bed down flow reactor. The reactor used for powder testing had an inner diameter of 5 mm. Typical catalyst loading was 0.06 g of 70-100 mesh powder. When testing engineered catalyst, two catalysts were separated by a spacer and were placed in a channel having dimensions 2"x 0.37"x 0.05", 5 cm x 0.94 cm x 0.13 cm) that is located in (i.e., a

rectangular aperture machined in) the center of a stainless steel catalyst holder (diameter 0.5 inch, 1.3 cm). The spacer held the catalyst against the walls of the channel. Steam reforming was conducted at between 220-475 °C and room pressure. Prior to testing, the catalysts were reduced in a 10 hydrogen stream at a temperature of 125 to 350 °C. A mixture of N₂ and H₂ were fed during startup to establish steady state flow and to heat the reactor to the operating temperature. When the catalyst bed reached the target temperature, premixed water and methanol at a ratio of 1.78 were vaporized in a preheater and fed into the reactor. Hydrogen flow was discontinued while nitrogen flow continued to stabilize flow. Feed rate is set to give desired contact time. When desired contact time is 100 msec, total flow rate should be set at 363 ml/min. The reaction products were analyzed by on-line gas chromatography. Methanol conversion is calculated based on feed and product flow rates and carbon balance.

A catalyst composed of about 70 wt% alumina, about 20 wt% zinc oxide, and 10 wt% Pd was tested as a powder and on a felt. The powder was tested at 1 atmosphere, 280 °C, a contact time of 100 msec and a LHSV of 30.5 h⁻¹, and achieved a productivity of 29,000 ml H₂ / ml catalyst·hr. The engineered catalyst was tested at 1 atmosphere, 300 °C, a contact time of 150 msec and a LHSV of 130 h⁻¹, and achieved a productivity of 90,000 ml H₂ / ml catalyst·hr (based on catalyst volume, not reaction chamber volume). To test the effect of Pd loading levels, powder catalysts having 1, 5, 10 and 15 wt% Pd were tested at 1 atmosphere, 294 °C, a contact time of 100 msec and a LHSV of 28 h⁻¹; these catalysts were found to have productivities of 13,300, 19,400, 19,500 and 20,600 ml H₂ / ml catalyst·hr, respectively. Indicating that at 5 wt% Pd and above, Pd loading levels have very little impact on productivity.

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CLOSURE

While preferred embodiments of the present invention have been shown and described, it will be apparent to those skilled in the art that many changes and modifications may be made without departing from the invention in its broader aspects.

The appended claims are therefore intended to include all such changes and modifications as fall within the true spirit and scope of the invention.